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WIND FACTOR SIMULATION MODEL: MODEL DESCRIPTION.(U)
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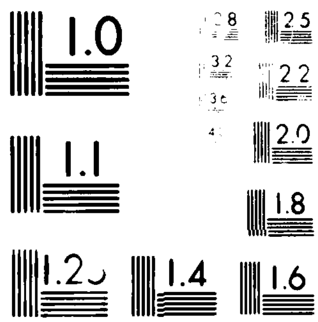
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LEVEL III

WIND FACTOR SIMULATION MODEL

Model Description

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UNITED STATES AIR FORCE
AIR WEATHER SERVICE (MAC)

USAF ENVIRONMENTAL
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A simplified, small and efficient Wind Factor Simulation (WFSM) is developed for inclusion in a Military Airlift Command (MAC) airlift system simulation called COLOSSUS. The WFSM calculates climatological wind factors by Sawyer's equivalent headwind technique for arbitrary great circle routes at specified altitudes for any of four seasons in any of three wind options. This technique is combined with the mathematics of great circle navigation in a constellation of seven FORTRAN subprograms. In the WFSM, a simulated aircraft is navigated along a great circle route between any two points on the globe. (Cont'd)

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20. ABSTRACT (Cont'd)

Involved in the mathematics of the navigation is solving the equation of a great circle. This equation is sometimes transcendental. In those cases, Newton's iterative method for the solution of nonlinear algebraic equations is used. he WFSM also calculates the great circle distance in nautical miles and the initial heading in degrees of any two points whose latitude and longitude are known.

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Chapter 1

INTRODUCTION

This technical note describes a simplified, computer efficient, Wind Factor Simulation Model (WFSM) developed by the United States Air Force Environmental Technical Applications Center (USAFETAC) in response to a request for such a model by the Military Airlift Command (MAC). MAC desired this model for inclusion in their large scale airlift system simulation effort, COLOSSUS.

The WFSM calculates climatological wind factors by Sawyer's equivalent headwind technique (Air Weather Service, 1977) for arbitrary great circle routes at specified altitudes for any of four seasons of the year in any of three modes or wind options (calm wind, mean wind, and 90-percent worst wind). In its present form the WFSM does not provide climb or descent winds. Nor does it provide temperatures and aircraft performance/fuel consumption information. The simulated wind option, intended to provide variability in the winds, has not been implemented, and requests for the simulated wind are treated as requests for the mean winds.

The Wind Factor Simulation Model consists of seven FORTRAN subprograms totaling approximately 2500 lines of source code, including extensive comments. The package includes subprograms for calculating great circle distance and initial great circle heading. Procedure plus data for the seven subprograms occupy 5.1K words of core storage on a 36-bit general purpose computer. The WFSM assumes that a wind data base has been read from a tape or disk file into a COMMON block. Hence, core storage for a file control block and buffer must be added to the above total to obtain a realistic estimate of the core storage required to run the wind factor model. Obtaining a wind factor for a long route requires approximtely 0.1-0.5 seconds central processing unit (CPU) time on a Honeywell 6080 general purpose computer.

Chapter 2

WIND FACTOR SIMULATION REQUIREMENTS

2.1 General

Requirements stipulated for the Wind Factor Simulation Model (WFSM) were originally quite extensive. Negotiations with the user reduced this list of requirements to those stated below. In the future, a number of the original requirements removed by negotiation are expected to reappear. Anticipated future requirements are discussed in section 2.5 below.

2.2 Required Outputs

The WFSM must produce simulated route-mean wind factors for reasonably arbitrary great circle routes between point "A" (takeoff) and point "B" (landing) at either of two constant altitudes (25,000 ft and 35,000 ft) for any of the four seasons of the year (winter, spring, summer, and fall) in any of three modes or wind options: (a) calm wind, (b) mean wind, and (c) 90-percent worst wind. A fourth mode, the simulated wind case, is one of the future requirements discussed in section 2.5 below. If simulated winds are requested by the user, mean winds will be provided.

Specifically, the Wind Factor Simulation Model must output the route-mean ground speed in knots (kt) for a given route-mean airspeed in knots and calculated route-mean wind factor in knots. In addition, the model must calculate the great circle distance (GCD) in nautical miles (NM) between any two points whose global (latitude/longitude) coordinates are known.

A capability possessed by the model because of internal needs, but not specifically requested by the user, is the ability to calculate the initial heading in degrees along a great circle route between any points whose global coordinates are known. Table 1 provides a general summary of WFSM outputs. More specific output descriptions are provided in Chapter 5.

TABLE 1. SUMMARY OF MODEL OUTPUTS.

Required/Internally Needed Quantity	Units
Route-mean ground speed	kt
Great circle distance (GCD)	NM
Initial great circle heading	deg

2.3 Inputs Provided

A user employing the WFSM to calculate a route-mean wind factor and ground speed must stipulate the global (latitude/longitude) coordinates of points "A" (takeoff) and "B" (landing), the Julian base date (1-366) of the wind factor request (used to determine season of the year), aircraft altitude (25,000 ft or 35,000 ft), mode or wind option (calm, mean, or 90-percent worst) and airspeed in knots.

To accommodate future growth the user must also stipulate Greenwich mean base time (0.0-24.0) of the wind factor request and forecast hours ahead of the wind factor required.* Presently, these inputs are ignored and may have any value. Table 2 provides a general summary of WFSM inputs. More specific descriptions are provided in Chapter 5.

*Greenwich mean base time is the Greenwich mean time for which the wind factor is desired. In the present WFSM, Greenwich mean base time is the same as Greenwich mean time. Future, more sophicated versions of the WFSM will produce wind factor forecasts. Then the Greenwich mean base time will be the Greenwich mean base time for which the wind factor forecast is desired minus the number of forecast hours ahead.

TABLE 2. SUMMARY OF MODEL INPUTS.

Required Quantity	Units
Latitude of point "A" (takeoff)	decimal deg
Longitude of point "A" (takeoff)	decimal deg
Latitude of point "B" (landing)	decimal deg
Longitude of point "B" (landing)	decimal deg
Julian base date (1-366)	none
Greenwich base time (0.0-24.0)	hr
Forecast hours ahead	hr
Altitude index (1 = 25,000 ft, 2 = 35,000 ft)	none
Wind option or mode (0 = calm wind, 2 = 90-percent worst wind, 3 = mean wind)	none
Airspeed	kt

2.4 Restrictions Imposed

The WFSM was originally constrained to operate within 1.5K words of core storage. This restriction was not met. The model now requires 5.1K plus file control block and buffer.

2.5 Future Requirements

Simulation models such as MAC's COLOSSUS, in which the WFSM must reside, have to approximate the major actions and decisions made in operational practice. Some of these operator decisions are based on climatology, some on forecasts, and some on observations. In the present model the day-to-day wind "observations" are always mean or climatologically expected values. There is no day-to-day variability in the "observed" winds. Furthermore, the model cannot simulate wind or wind factor "forecasts."

When the "observed" winds always correspond to a climatologically expected value the upper atmosphere wind flow does not change. It is more realistic to permit a day-to-day variability in the wind factor, a variability that is the statistical analog of the natural evolution of upper-air wind patterns. Future requests will doubtless state a requirement for "simulated" wind factors having a natural variability. The architecture of subroutine ENRWND will accomodate a "simulated" wind factor technique. The present subroutine defaults to the mean wind factor case.

Future requests may include a requirement for "forecast" winds. If climatology, "forecasts," and "observations" are all realistically included in the WFSM, users of that model can determine, in the larger context of their own mission simulations, the optimum mix of climatology, forecasts, and observations.

Chapter 3

WIND FACTOR SIMULATION MODEL

3.1 General Description of the Method and Overall Simulation Logic

Sawyer's equivalent headwind technique (Air Weather Service, 1977) is combined with the mathematics of great circle navigation in a constellation of seven FORTRAN subprograms whose purpose is given in Table 3.

TABLE 3. WIND FACTOR SIMULATION MODEL SUBPROGRAMS.

Subprogram	Purpose
ENRWND	Main enroute wind factor subprogram called directly by user to compute ground speed from given airspeed in any of three modes for two flight levels and four seasons of the year.
DISTAN	Called by ENRWND and HDG or directly by user to compute great circle distance in NM between any two points on the globe.
SPHGLO	Conversion of spherical coordinates to global latitude and longitude or vice versa. Called by GRTCIR.
GRTCIR	Solution of great circle equation for latitude given longitude, or for longitude given latitude. Called by ENRWND.
HDG	Calculation of initial heading along a great circle route flown from a given origin to a given destination. Called by ENRWND and GRTCIR.
BRLNG	For a spherical grid system whose longitude boundaries are spaced at 30° intervals, finds the longitude grid values bracketing a given arbitrary longitude. Called by ENRWND.
BRLAT	For a spherical grid system whose latitude boundaries are spaced at 15° intervals, finds the latitude grid values bracketing a given arbitrary latitude. Called by ENRWND.

The keystone subprogram of the Wind Factor Simulation Model is ENRWND, which handles most of the aircraft navigation except solution of the equation of a great circle and also accomplishes all of the meteorological computations of the wind factor.

The ENRWND subprogram navigates a simulated aircraft over a great circle route from point "A" to point "B" in a global (latitude/longitude oriented) grid system whose resolution is 15° latitude by 30° longitude. The subroutine determines the grid sector location of the aircraft and then determines the length of the aircraft's path through the sector. Next, the routine consults the wind data base for the particular grid sector, flight level, and season to obtain sector-mean wind direction, speed, and variance. Cross-track and along-track components of the wind are computed. These components are weighted by the length of the aircraft's track through the sector and are accumulated. At the end of the simulated flight, the accumulators are divided by the total GCD for the flight, producing a distance-weighted, route-mean cross-track wind component, an along-track component, and a variance. From these components a route-mean wind factor is computed. If the 90-percent worst wind option has been selected, that wind factor is statistically adjusted to the 10-percent risk value. The wind factor is then added to the airspeed to obtain the route-mean airspeed. If the calm wind option is requested, all of these computations are bypassed, and a zero wind factor is used. Requests for the simulated wind option default to the mean wind. In this case, the mean wind is

developed directly from the mean wind data base. In the 90-percent worst case, this mean wind factor is statistically adjusted to a value such that only 10 percent of flights over that route will experience a worse wind factor (10-percent risk).

3.2 Sawyer's Equivalent Headwind Technique

Leg and overall route wind factors are computed by Sawyer's equivalent headwind technique (as described in Section 3.1).

A wind factor W can be defined as the difference between the ground speed $|\vec{G}|$ of an aircraft and its true airspeed $|\vec{A}|$. This relationship is given in the equation:

$$W = |\vec{G}| - |\vec{A}| = G - A \tag{1}$$

Sawyer found that a mean or climatological overall wind factor for a route is given by the relationship:

$$[\overline{W}] = [\overline{U}] - \frac{1}{2A}\left([\overline{V}^2] + \frac{[\sigma^2]}{2}\right) \tag{2}$$

where [] indicates an average over all the legs, and where

$\overline{W}$ = mean wind factor

$\overline{U}$ = mean wind component along aircraft track

$\overline{V}$ = mean crosswind component

⋮

σ^2 = mean variance

The first term to the right of the equal sign in Eq. (2) is the tailwind component, and the second term is the effect of the crosswind.

In calculating the 90-percent worst wind factor (i.e., 10-percent risk), Sawyer used the equation:

$$W_{90\%} = [\overline{W}] - 1.28\ \sigma_W \tag{3}$$

where σ_W is related to $[\sigma]$ by the Sawyer K-factor. This K-factor is route length dependent and is expressed as

$$K = \frac{\sigma_W}{[\sigma]} \tag{4}$$

Sawyer provides a table of K as a function of route length. For convenience, a geometric curve was fitted to Sawyer's tabular data using the Hewlett-Packard 65 Stat Pac 2 curve fit program (Hewlett-Packard Company, 1975c). The curve is

$$K = 0.70585066 \times (0.99983056)^d \tag{5}$$

where d = great circle distance in nautical miles.

3.3 Grid System

The WFSM must be economical in terms of computer core storage and run time; yet it must provide a global wind factor capability to the user. These conflicting requirements dictated the use of a coarse grid. The original idea, motivated by the

latitude/longitude orientation of the winds used as input data, was to have a grid system in global (latitude/longitude) coordinates. A grid would have a spacing of 15° latitude by 30° longitude and would cover the globe, requiring 144 grid sectors (12 sectors from pole to pole times 12 sectors around the equator). Closer investigation of the latitudes of the COLOSSUS terminals and routes indicated that grid sectors were not necessary above 75°N and below 60°S. Since three quantities (wind direction, speed, and variance) are stored for each grid sector for four seasons and two flight levels, approximately 0.87K words of core storage could be saved by reducing the number of grid sectors from 144 to 108.

The grid system chosen for implementation is in global (latitude/longitude) coordinates, with a resolution of 15° latitude by 30° longitude. The grid system extends from 75°N to 60°S (9 rows) and globally in longitude (12 columns). Hence, there are 108 grid sectors as shown in Figure 1. Note that column 1 is keyed on 30°W not 0°.

Column # →

Row # ↓	1	2	3	4	5	6	7	8	9	10	11	12
1	1	2	3	4	5	6	7	8	9	10	11	12
2	13	14	15	16	17	18	19	20	21	22	23	24
3	25	26	27	28	29	30	31	32	33	34	35	36
4	37	38	39	40	41	42	43	44	45	46	47	48
5	49	50	51	52	53	54	55	56	57	58	59	60
6	61	62	63	64	65	66	67	68	69	70	71	72
7	73	74	75	76	77	78	79	80	81	82	83	84
8	85	86	87	88	89	90	91	92	93	94	95	96
9	97	98	99	100	101	102	103	104	105	106	107	108

75°N 60°N 30°N 0° 30°S 60°S

0° 90°E 180° 90°W

Figure 1. Grid System.

Because this grid system does not include the poles, the Wind Factor Simulation model cannot consider over-the-pole flights. The coarseness of the grid system precludes use of this model for calculation of operational wind factors. The coarse grid is suitable for simulation, however, and could be made finer if improved meteorological resolution is desired.

3.4 Data Base

Basic data for the WFSM are the USAFETAC Single Integrated Operations Plan (SIOP) winds. With a period of record extending from January 1972 to December 1976, the SIOP winds contain mean u-component, v-component, and vector standard deviation tabulated on a 5-degree offset grid. This grid is much finer than that used by the WFSM.

To prepare a data base for the Wind Factor Simulation Model's 15° latitude by 30° longitude grid system, simple averaging was used. The u-component, the v-component, and the vector standard deviation were averaged separately. The average was performed by extracting from the SIOP winds three values latitudinally and six values

longitudinally. The resulting 3 x 6 = 18 values were summed and the sum divided by 18 to obtain the mean data values for each grid sector. In this way, mean u-components, v-components, and vector standard deviations were obtained for all 108 grid sectors. Such a data base was constructed for January (winter), April (spring), July (summer), and October (fall) for altitudes 25,000 feet (taken from 400-mb winds) and 35,000 feet (taken from 250-mb winds). Using an in-house USAFETAC program WIND, the

4 season x 2 altitude = 8 sets

of 108-sector wind data were converted from u-components, v-components, and vector standard deviation to direction (beta angle, described in Appendix B), speed, and variance. After conversion, the winds were stored sequentially in a data file in the order described in Table 4. The data file consists of 864 records (4 seasons x 2 altitudes x 108 sectors). Each sector of the data file requires one record of disk storage containing the three elements of information shown in Table 5.

TABLE 4. STRUCTURE OF WIND DATA FILE.

Season	Flight Level (hundreds of feet)	Number of Sectors	Record Numbers
Winter	250	108	1 - 108
	350	108	109 - 216
Spring	250	108	217 - 324
	350	108	325 - 432
Summer	250	108	433 - 540
	350	108	541 - 648
Fall	250	108	649 - 756
	350	108	757 - 864

TABLE 5. FORMAT OF WIND DATA RECORD.

ELEMENT	UNITS	COLUMNS	FORTRAN FORMAT
Wind Direction (Beta Angle)	radians	1 - 15	F15.5
Wind Speed	knots	16 - 30	F15.5
Variance	knots^2	31 - 45	F15.5

To be used by the Wind Factor Simulation Model, the data base must be loaded from the data file into the arrays:

DIR(870) Wind direction beta angle (radians)

SPD(870) Wind speed (knots)

VAR(870) Wind variance (knots^2)

These arrays are located in the labeled COMMON block WEA and require 2.6K words of computer core storage. The COMMON block must be loaded with wind data before the WFSM is first executed. Usually an initializing routine external to the WFSM is used for this purpose. That routine reads 864 wind records in order and stores them, without rearrangement, in the COMMON block WEA. Thereafter, the wind data base can be accessed in terms of a record number NRND as follows:

DIR(NRND) SPD(NRND) VAR(NRND)

The record number NRND is computed by:

$$\begin{aligned} NRND = &(\text{Season Index} - 1) * (\text{Total Number Altitudes}) \\ &* (\text{Total Number Grid Sectors}) \\ &+ (\text{Altitude Index} - 1) * (\text{Total Number Grid Sectors}) \\ &+ (\text{Sector Number}) \end{aligned} \tag{6}$$

3.5 Aircraft Navigation Technique and Logic

Aircraft navigation is handled principally by the subroutine ENRWND. The subroutine subprogram GRTCIR solves the equation of a great circle.

The simulated aircraft is navigated along a great circle route between points "A" and "B" by moving from a point called the "Current-Point" (XLATC, XLNGC) to a point called the "Next-Point" (XLATNP, XLNGNP). Most of the computation of the Next-Point is done in global (latitude/longitude) coordinates.

For any given Current-Point, the Next-Point is either the point where the great circle route crosses a latitude grid line (0, 15, 30, ..., deg) or the point where a route crosses a longitude grid line (0, 30, 60, ..., deg), whichever is closer to the Current-Point. This is illustrated in Figure 2.

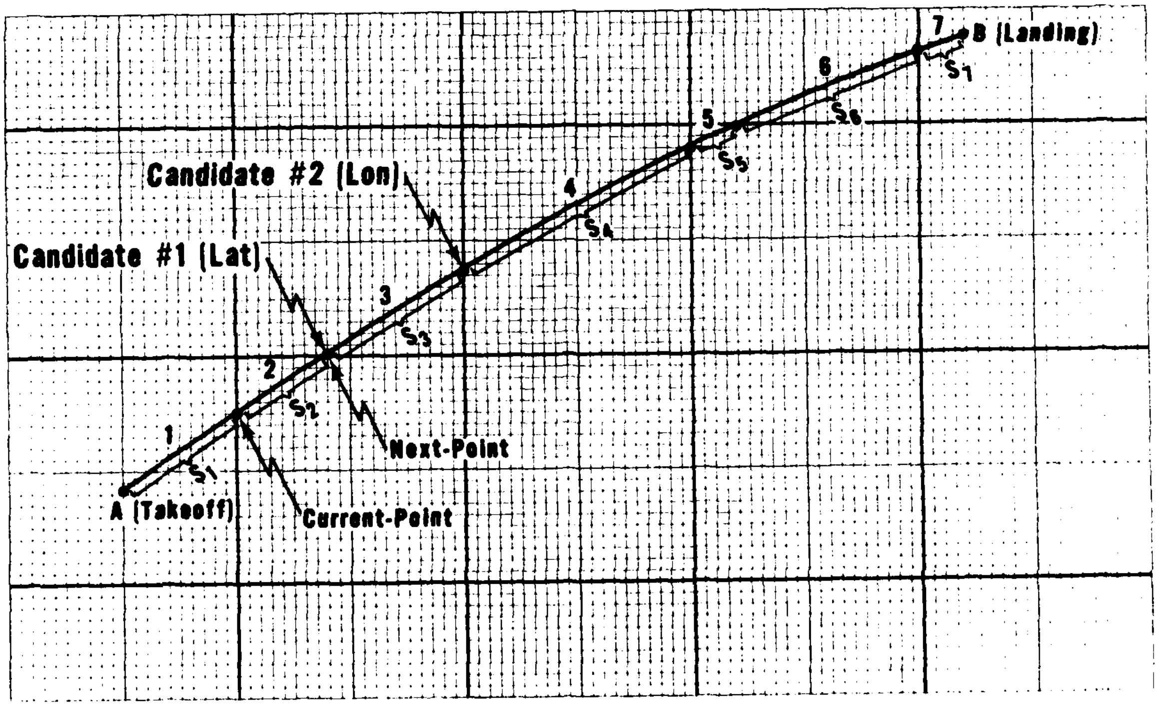

Figure 2. Aircraft Navigation Technique.

At the Current-Point the aircraft's heading can be calculated via the heading formula (function HDG). Knowledge of the location of the Current-Point and the aircraft's heading at that point dictates the next latitude crossing and the next longitude crossing. Candidate #1 for the Next-Point is the point of next latitude crossing, XLATNX (and associated longitude, XLNGAS). Candidate #2 is the point of next longitude crossing, XLNGNX (and associated latitude, XLATAS).

Calculation of longitude, XLNGAS, associated with a given latitude, XLATNX, is done iteratively by subroutine GRTCIR, which solves the equation of a great circle. Newton's iterative method with an exact spherical triangle first guess is used. Virtually all the complexity of subroutines GRTCIR and ENRWND is attributable to solving the equation of a great circle for longitude, given the latitude.

Calculation of latitude, XLATAS, associated with a given longitude, XLNGNX, is accomplished by subroutine GRTCIR.

Candidates for Next-Point are then as follows

Candidate #1	(XLATNX, XLNGAS)
Candidate #2	(XLATAS, XLNGNX)

With Candidates #1 and #2 identified, subroutine DISTAN is then used to calculate great circle distances as follows:

S1	GCD from Current-Point to Candidate #1
S2	GCD from Current-Point to Candidate #2

The candidate with the shorter distance, S1 or S2, is selected as the Next-Point.

The Current-Point can then be thought of as the point where the aircraft enters the grid sector, and the Next-Point as the point where the aircaft departs the sector. The distance between Current-Point and Next-Point, SNP, is the distance by which the wind components and variance are weighted in computing the route-mean wind factor.

3.6 Meteorological Technique and Logic

Subroutine ENRWND calulates the meteorological quantities required by the Wind Factor Simulation Model.

With Current-Point and Next-Point established, an appropriate midpoint (XLATM, XLNGM) between them is computed. The number, NSEC, indicating which of the 108 grid sectors through which the aircraft is passing is then calculated based on (XLATM, XLNGM). See the description of the grid system in section 3.3 above. Since four seasons and two flight levels, as well as 108 grid sectors are provided for, a datum number (NRND) is obtained from the grid sector number (NSEC, values 1-108), the altitude index (IALT, values 1-2) and the season index (ISEASN, values 1-4) using Eq. (6).

With the datum number, NRND, calculated, the data base (see description in section 3.4) is consulted to obtain sector-mean wind direction (DIRM, radians in beta angle form, as described in Appendix B), speed (SPDM, knots), and variance (VARM, knots^2):

$$\begin{aligned} DIRM &= DIR(NRND) \\ SPDM &= SPD(NRND) \\ VARM &= VAR(NRND) \end{aligned} \tag{7}$$

Function HDG computes the aircraft heading (HDGM) at (XLATM, XLNGM) in beta angle format (see Appendix B). In that format HDGM is represented by the angle ALPHA.

ALPHA, the wind direction, DIRM, and the wind speed, SPDM, are used to calculate the along-ground-track wind component, VGM, and the cross-ground-track wind component, VCM:

$$VGM = SPDM \times COS\ (ABS(DIRM - ALPHA)) \tag{8}$$

$$VCM = SPDM \times SIN\ (DIRM - ALPHA) \tag{9}$$

A time-averaged wind factor for the present leg (WBAR) is then computed using Sawyer's equivalent headwind formula, Eq. (2). No further use is made of WBAR.

The quantities VGM, VCM, and VARM are multiplied by the sector or leg length, SNP, and the product is accumulated in VGACC, VCACC, and VACC. Then the Next-Point becomes the Current-Point, and a new Next-Point is calculated. The process is repeated for the next leg of the simulated flight.

After the last leg of the flight has been processed, the accumulators VGACC, VCACC, and VACC are divided by the total route length. The resultant distance-weighted along-track, cross-track, and variance quantities are then used in the Sawyer equivalent headwind formula, Eq. (2), to obtain the distance-weighted, route-mean wind factor, WBARBR. To obtain the 90-percent worst wind factor, WBARBR is statistically adjusted to the 90-percent worst value by Sawyer's technique.

As part of the wrap-up actions of subroutine ENRWND, the route-mean wind factor, WBARBR, is added to the airspeed, ASPEED, to get a ground speed, GSPEED, for return to the program calling subroutine ENRWND.

3.7 Equation of a Great Circle

In the wind factor simulator, great circle routes are flown from point "A," the origin, to point "B," the destination. A great circle is the intersection of a sphere and a plane passing through the center of the sphere, shown in Figure 3. As a mathematical curve, the great circle must be representable in terms of an equation. One such equation may be developed from vector algebra as follows.

Consider that $\vec{Q}_A$ is the position vector from the center of the sphere to point "A" along the great circle, while $\vec{Q}_B$ is the position vector of point "B." The plane of the great circle is defined by the vector cross product:

$$\vec{Q}_T = \vec{Q}_A \times \vec{Q}_B \tag{10}$$

where $\vec{Q}_T$ is normal to the plane.

Let $\vec{Q}$ be the position vector of any intermediate point "D" along the great circle. Since $\vec{Q}_T$ is normal to $\vec{Q}$, an equation describing the great circle is

$$\vec{Q} \cdot (\vec{Q}_A \times \vec{Q}_B) = 0 \tag{11}$$

Points "A", "B", and "D" are ordinarily described in terms of latitude and longitude, which are here called global coordinates. Global coordinates are easily

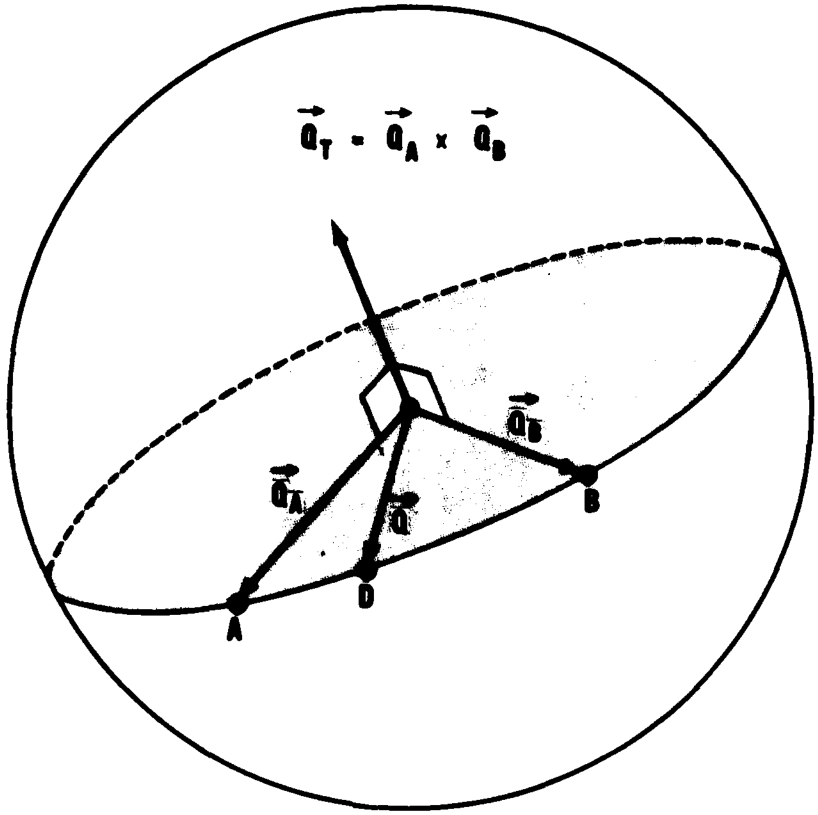

Figure 3. Plane of the Great Circle.

transformed into spherical coordinates, shown in Figure A-1. The transformation is given in Appendix A of this report. Using these transformations the vectors $\vec{Q}$, $\vec{Q}_A$, and $\vec{Q}_B$ are given in rectangular coordinates by

$$\left.\begin{aligned} \vec{Q}_A &= Q_{Ax}\vec{i} + Q_{Ay}\vec{j} + Q_{Az}\vec{k} \\ \vec{Q}_B &= Q_{Bx}\vec{i} + Q_{By}\vec{j} + Q_{Bz}\vec{k} \\ \vec{Q} &= Q_x\vec{i} + Q_y\vec{j} + Q_z\vec{k} \end{aligned}\right\} \quad (12)$$

where

$$\left.\begin{aligned} Q_{Ax} &= r \sin \theta_A \cos \varphi_A = rq_{Ax} \\ Q_{Ay} &= r \sin \theta_A \sin \varphi_A = rq_{Ay} \\ Q_{Az} &= r \cos \theta_A = rq_{Az} \end{aligned}\right\} \quad (13)$$

$$\left.\begin{aligned} Q_{Bx} &= r \sin\theta_B \cos\varphi_B = rq_{Bx} \\ Q_{By} &= r \sin\theta_B \sin\varphi_B = rq_{By} \\ Q_{Bz} &= r \cos\theta_B \qquad\quad = rq_{Bz} \end{aligned}\right\} \tag{14}$$

$$\left.\begin{aligned} Q_x &= r \sin\theta \cos\varphi = rq_x \\ Q_y &= r \sin\theta \sin\varphi = rq_y \\ Q_z &= r \cos\theta \qquad\quad = rq_z \end{aligned}\right\} \tag{15}$$

and where

$$\left.\begin{aligned} q_{Ax} &= \sin\theta_A \cos\varphi_A \\ q_{Ay} &= \sin\theta_A \sin\varphi_A \\ q_{Az} &= \cos\theta_A \end{aligned}\right\} \tag{16}$$

$$\left.\begin{aligned} q_{Bx} &= \sin\theta_B \cos\varphi_B \\ q_{By} &= \sin\theta_B \sin\varphi_B \\ q_{Bz} &= \cos\theta_B \end{aligned}\right\} \tag{17}$$

$$\left.\begin{aligned} q_x &= \sin\theta \cos\varphi \\ q_y &= \sin\theta \cos\varphi \\ q_z &= \cos\theta \end{aligned}\right\} \tag{18}$$

The cross product is

$$\vec{Q}_T = \vec{Q}_A \times \vec{Q}_B = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ rq_{Ax} & rq_{Ay} & rq_{Az} \\ rq_{Bx} & rq_{By} & rq_{Bz} \end{vmatrix} \tag{19}$$

or

$$\vec{Q}_T = r^2 \left[(q_{Ay}\, q_{Bz} - q_{Az}\, q_{By})\, \vec{i} + (q_{Az}\, q_{Bx} - q_{Ax}\, q_{Bz})\, \vec{j} \right.$$

$$\left. + (q_{Ax}\, q_{By} - q_{Ay}\, q_{Bx})\, \vec{k}\right]$$

$$\vec{Q}_T = r^2 \, (q_{Tx}\, \vec{i} + q_{Ty}\, \vec{j} + q_{Tz}\, \vec{k}) \tag{20}$$

where

$$\left.\begin{aligned} q_{Tx} &= q_{Ay}\, q_{Bz} - q_{Az}\, q_{By} \\ q_{Ty} &= q_{Az}\, q_{Bx} - q_{Ax}\, q_{Bz} \\ q_{Tz} &= q_{Ax}\, q_{By} - q_{Ay}\, q_{Bx} \end{aligned}\right\} \tag{21}$$

The vector equation of the great circle is

$$\vec{Q} \cdot \vec{Q}_T = 0 \tag{22}$$

or in component form,

$$q_x\, q_{Tx} + q_y\, q_{Ty} + q_z\, q_{Tz} = 0 \tag{23}$$

where q_{Tx}, q_{Ty}, and q_{Tz} are known from points "A" and "B." Substituting for q_x, q_y, and q_z gives the results,

$$(\sin\theta \cos\varphi)\, q_{Tx} + (\sin\theta \sin\varphi)\, q_{Ty} + (\cos\theta)\, q_{Tz} = 0 \tag{24}$$

which is the equation of a great circle in rectangular component form.

Two solutions of the equation of a great circle are possible:

Case 1: Solve for θ with φ known

Case 2: Solve for φ with θ known

For Case 1, a deterministic solution can be obtained by dividing the great circle equation by $\sin\theta$:

$$q_{Tx} \cos\varphi + q_{Ty} \sin\varphi + \frac{q_{Tz}}{\tan\theta} = 0 \tag{25}$$

or

$$\theta = \tan^{-1}\left(\frac{-q_{Tz}}{q_{Tx} \cos\varphi + q_{Ty} \sin\varphi}\right) \tag{26}$$

which is easily evaluated and solved, since q_{Tx}, q_{Ty}, q_{Tz}, and φ are known.

Case 2 proves more difficult to solve in that it takes the form of a transcendental equation. Newton's iterative method (sometimes called the Newton-Raphson method) for the solution of nonlinear algebraic equations was selected as the numerical technique with which to solve the great circle equation for φ, where θ is known.

3.8 Newton's Iterative Method

The zeros or roots of the nonlinear function,

$$f(\varphi) = 0 \tag{27}$$

in Newton's method, are found by the recursion relation,

$$\varphi^{(n+1)} = \varphi^{(n)} - \frac{f[\varphi^{(n)}]}{f'[\varphi^{(n)}]} \tag{28}$$

where n is the iteration count and f' is the first derivative of the function. In the case of the great circle formula in the form of Eq. (27),

$$f(\varphi) = q_{Tx} \cos \varphi + q_{Ty} \sin \varphi + \frac{q_{Tz}}{\tan \theta} \tag{29}$$

$$f'(\varphi) = -q_{Tx} \sin \varphi + q_{Ty} \cos \varphi \tag{30}$$

Newton's method requires a first guess, $\varphi^{(0)}$. The first guess must be "close enough" to the real root to insure convergence of the method, which then is quite rapid, with the number of good decimal digits nearly doubling at each iteration. If the first guess is not close enough, Newton's method may diverge. For the great circle equation, the first guess, $\varphi(0)$, must be within about 35° (0.61 radians) of the true root to insure convergence. Methods for generating the first guess are discussed in the following section of this report.

3.9 First Guess Methods for Newton's Iterative Technique

Solving the transcendental equation for longitude (azimuth), given the latitude (colatitude), by Newton's iterative technique requires a first guess for the azimuth φ. In practice, obtaining this first guess is critical for convergence of Newton's technique, which otherwise may diverge or converge to false roots.

In subroutine GRTCIR, three methods are potentially used to obtain the first guess azimuth φ^g. The first such method, not normally used except in debugging, is for the user to specify the value of φ^g. The second method is that of approximately planar triangles. This method has important limits on its reliability and so is used only to find the longitude(s) where the great circle crosses the equator. The third, and most exact first guess method, is that of the exact spherical triangle. The spherical triangle method requires knowledge of the longitude of equator crossing and thus cannot be used initially.

In application for any given route, the approximate planar triangle method is used initially to obtain the longitude of equator crossing. Thereafter, the exact spherical triangle method is used throughout the route.

3.9.1 Method of Approximately Planar Triangle. A segment of a great circle is shown by the line EF in Figure 4, where the point E may be either the origin A of the flight or the destination B, whichever is closer to the equator. If E coincides with A, then F must coincide with B; if E coincides with B, then F must coincide with A. If the route is extended to the equator, the equator crossing point A' is defined as shown in Figure 4.

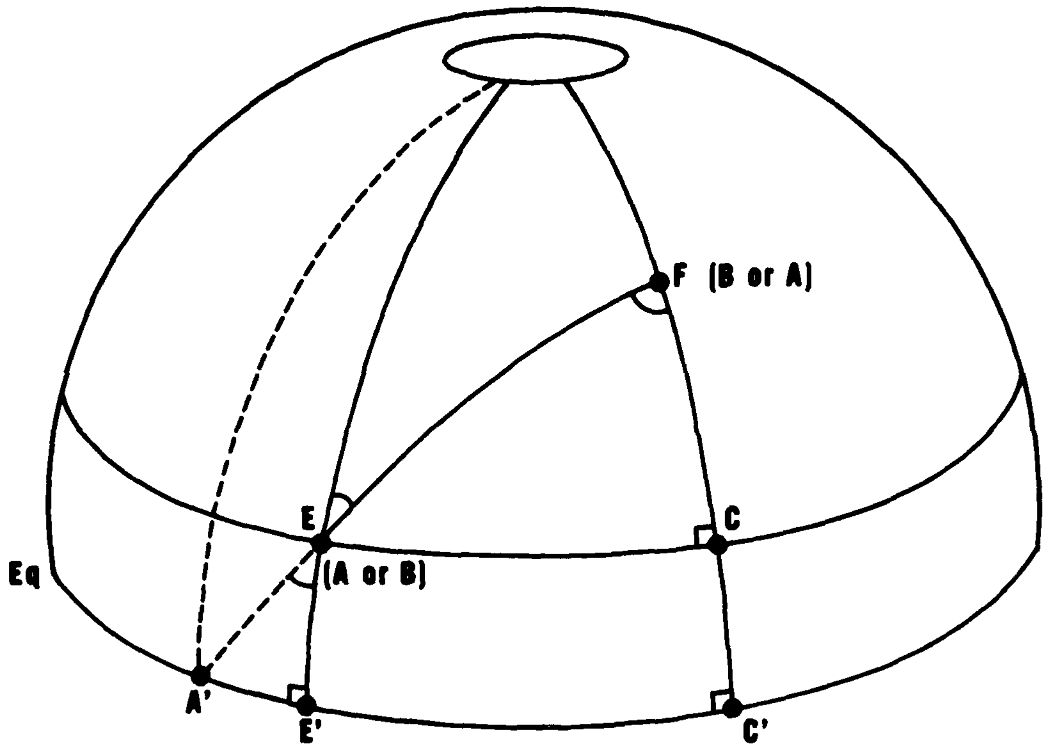

Figure 4. Approximately Planar Triangle.

The spherical triangle A'EE' must be solved for the arc $\overline{A'E'}$ in order to obtain the azimuth $\varphi_{A'}$ of the equator crossing point A'. Not enough infomation is known about this triangle to solve it spherically. If A'EE' is approximated by a planar right triangle, an approximation to the distance $\overline{A'E'}$ can be obtained through the tangent of the angle E, which is known from the heading of the aircraft at point E:

$$\overline{A'E'} \approx \overline{E'E} \tan E \qquad \text{(radians)} \tag{31}$$

But the angular distance $\overline{E'E}$ is simply the known latitude of point E in radians. Hence:

$$\overline{A'E'} \approx \mathrm{LAT}_E \tan E \qquad \text{(radians)} \tag{32}$$

and the first guess equator crossing azimuth is

$$\varphi^g_{A'} = \varphi_{E'} - \overline{A'E'} \qquad \text{(radians)} \tag{33}$$

The first guess $\varphi^g_{A'}$ is then improved to the final value of $\varphi_{A'}$ by Newton's iterative technique, described in paragraph 3.8 above.

3.9.2 Method of Exact Spherical Triangle. A segment of a great circle is shown as the line AB of Figure 5, where point A is the origin of the flight, and point B is its destination. Point D is any intermediate point along the $\overline{AB}$ great circle. The right spherical triangle of interest is A'DE', where point A' is the equator crossing established above, and the angular distance $\overline{DE'}$ is given by the known latitude of the intermediate point D.

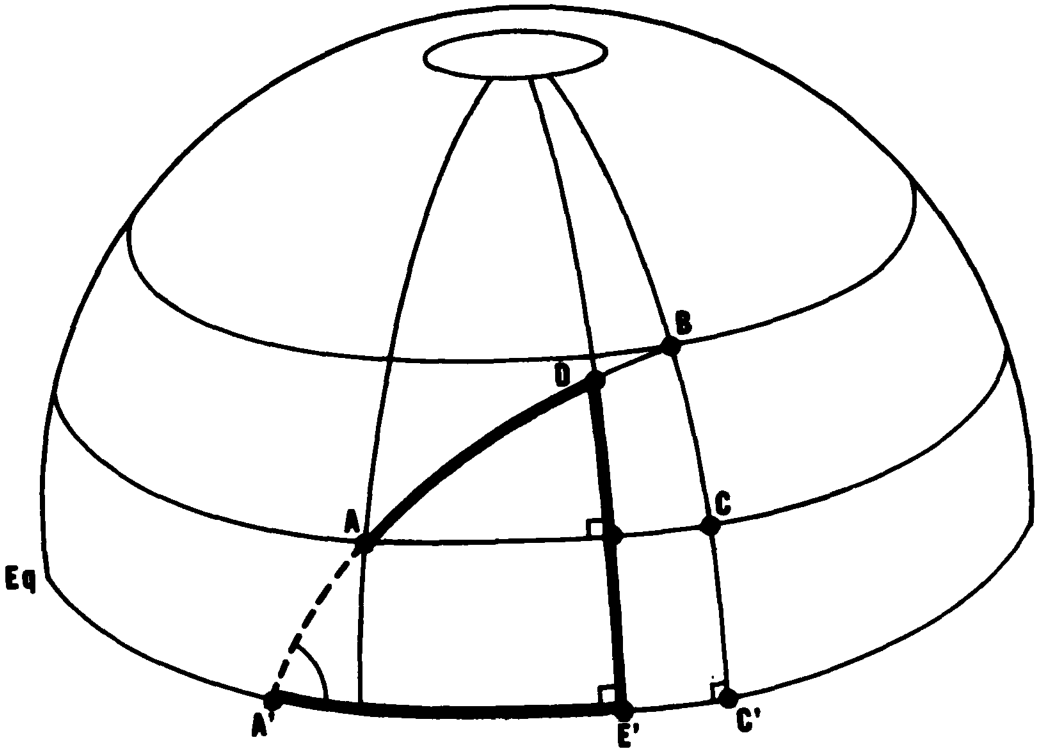

Figure 5. Spherical Triangle Opening Eastward.

Since the position of A' is known, the angle A' can be obtained from the heading of the aircraft at A'. The unknown of interest is the great circle angular distance $\overline{A'D}$.

The law of sines for spherical triangles gives the result:

$$\frac{\sin E'}{\sin \overline{A'D}} = \frac{\sin A'}{\sin \overline{DE'}} \quad (34)$$

or

$$\overline{A'D} = \sin^{-1}\left(\frac{\sin E' \cdot \sin \overline{DE'}}{\sin A'}\right) \quad \text{(radians)} \quad (35)$$

From the spherical right triangle it is known that the angle E' is 90°; hence:

$$\overline{A'D} = \sin^{-1}\left(\frac{\sin \overline{DE'}}{\sin A'}\right) \quad \text{(radians)} \quad (36)$$

for which there are solutions in all quadrants. In practice, the principal solution,

$$-\frac{\pi}{2} \le \overline{A'D_1} \le \frac{\pi}{2} \tag{37}$$

and the solution,

$$\overline{A'D_2} = \pi - \overline{A'D_1} \qquad \text{(radians)} \tag{38}$$

are of interest.

It is desirable to estimate the angular distance $\overline{A'E'}$. Since the azimuth $\varphi_{A'}$ of the equator crossing point A' is known, the problem of obtaining $\overline{A'E'}$ reduces to that of estimating the azimuth φ_D of the point D, which is the same as the azimuth $\varphi_{E'}$ of the point E'. The problem can be addressed in terms of longitude via the great circle distance formula:

$$\cos\ (LNG_D - LNG_{A'}) = \frac{\cos\ (\overline{A'D}) - \sin\ (LAT_{A'})\ \sin\ (LAT_D)}{\cos\ (LAT_{A'})\ \cos\ (LAT_D)} \tag{39}$$

But the latitude of the equator is 0°, so

$$LNG_D = LNG_{A'} \pm \cos^{-1}\left[\frac{\cos\ (A'D)}{\cos\ (LAT_D)}\right] \tag{40}$$

where the negative sign is used for the spherical triangle opening eastward (Figure 5), and the positive sign is used for the spherical triangle opening westward (Figure 6).

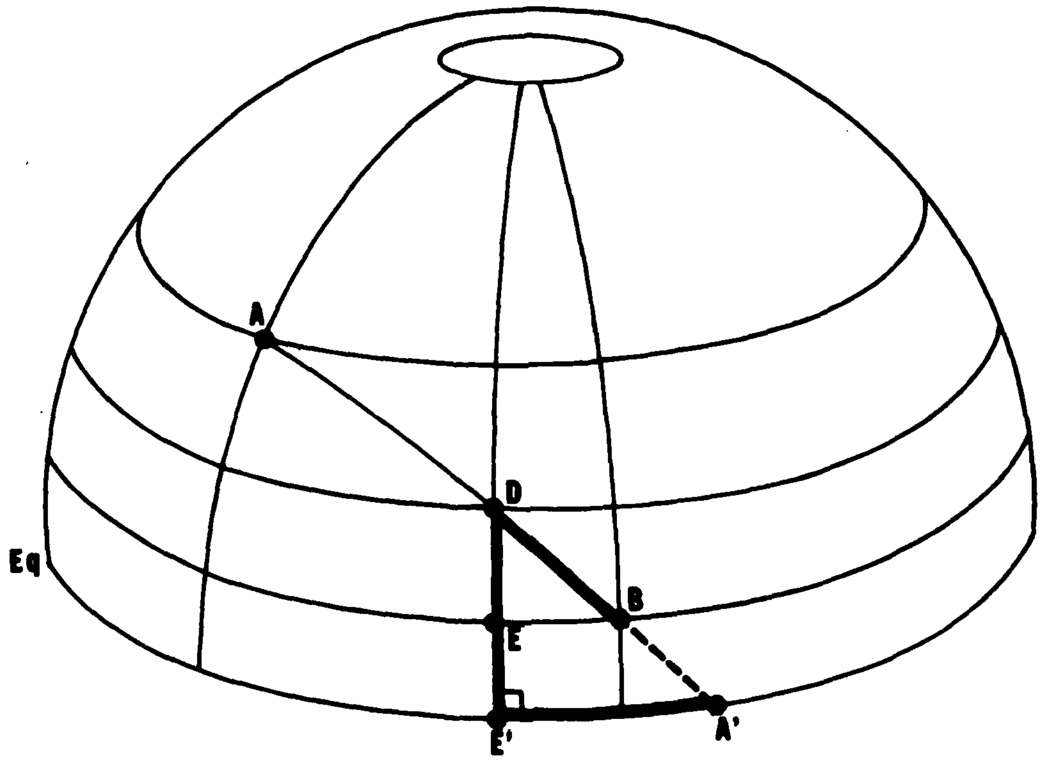

Figure 6. Spherical Triangle Opening Westward.

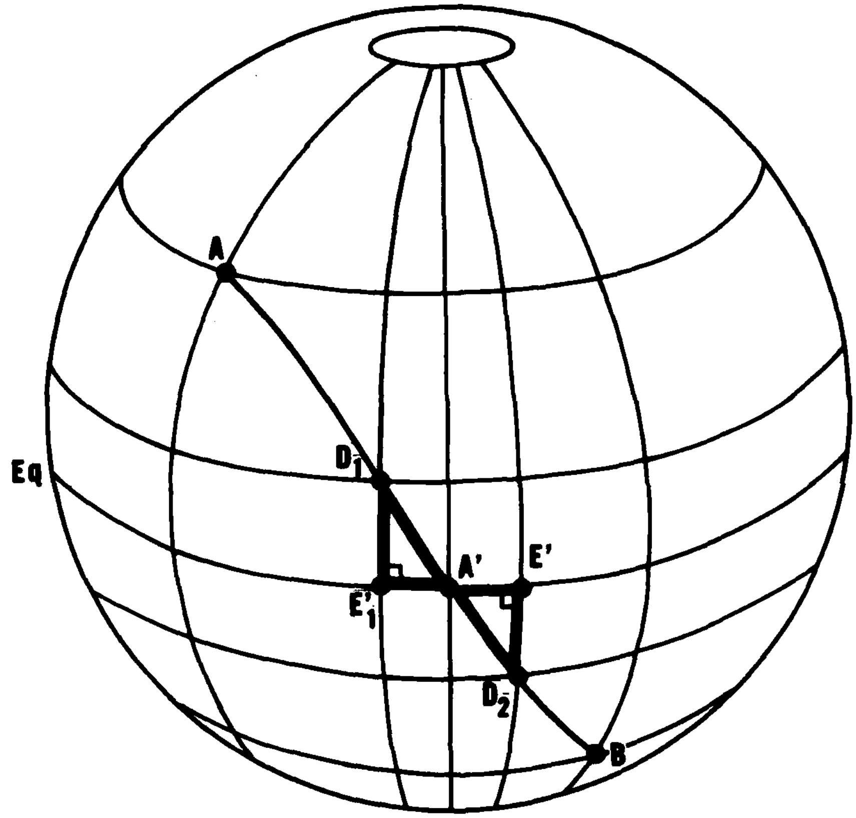

Figure 7. Route Crossing Equator Shows Reversal of Spherical Triangle.

The criterion for "opening eastward" is that point E' must be east of point A'. In a triangle that "opens westward", point E' is west of point A'. Routes that cross the equator exhibit reversal of the spherical triangle direction at the point of equator crossing, as shown in Figure 7.

3.10 Great Circle Distance

The Wind Factor Simulation Model (WFSM) computes the great circle distance (GCD) through its subroutine DISTAN. DISTAN was developed from a program of the Hewlett-Packard Company (HP). The HP-65 Navigation Pac 1 (Hewlett-Packard Company, 1975b) describes the method.

The basic equation for the great circle distance in radians is

$$GCD_r = \cos^{-1}[\sin(LAT_A)\sin(LAT_B)+\cos(LAT_A)\cos(LAT_B)\cos(LNG_B-LNG_A)] \quad (41)$$

where

LAT_A, LNG_A = coordinates of initial point "A" in radians

LAT_B, LNG_B = coordinates of final point "B" in radians

GCD_r = great circle distance in radians from "A" to "B"

To convert to GCD in nautical miles (NM), the relation,

$$GCD_m = a \cdot GCD_r \tag{42}$$

is used, where "a" is the radius of the earth in nautical miles (approximately 3440 NM).

DISTAN is employed for more than just computing GCDs from departure to destination. It is called by subroutine ENRWND every time the aircraft is ready to move from its Current-Point to the Next-Point along the great circle track. The Next-Point is always the candidate point with the shortest GCD between it and the Current-Point. DISTAN can be called as few as four times (route does not cross grid boundaries) or as many as 25 or more times depending upon route length and number of grid crossings.

3.11 Great Circle Heading

The WFSM computes the initial heading (degrees clockwise from north toward which the aircraft is moving) along a great circle route from point "A" to point "B" by means of the function subprogram HDG. This function was developed from the Hewlett-Packard 65 Aviation Pac 1, Great Circle Navigation (Hewlett-Packard Company, 1975a). The function uses input latitudes and longitudes for points "A" and "B" and converts them from degrees to radians, then uses the heading formula,

$$HDG_r = \cos^{-1}\left[\frac{\sin(LAT_B) - \sin(LAT_A)\cos(GCD_r)}{\sin(GCD_r)\cos(LAT_A)}\right] \tag{43}$$

to find the initial heading, HDG_r, in radians at point "A". The other variables are described in paragraph 3.10 above. The great circle distance in radians, GCD_r, is computed by use of subroutine DISTAN, which gives GCD_m in nautical miles. GCD_m is converted to GCD_r by the relation,

$$GCD_r = \frac{GCD_m}{a} \tag{44}$$

where "a" is the radius of the earth in nautical miles (approximately 3440 NM).

If

$$\sin(LNG_A - LNG_B) < 0 \tag{45}$$

then the first quadrant arc cosine solution is not desired. A correction is made by setting

$$HDG'_r = 2\pi - HDG_r \tag{46}$$

Then the heading in radians is converted to the heading in degrees by multiplying by $180/\pi$.

Chapter 4

MODEL CAPABILITIES AND LIMITATIONS

4.1 Model Capabilities

The Wind Factor Simulation Model (WFSM) is capable of producing mean overall wind factors for great circle routes. It does so in any of three modes: calm wind case, 90-percent worst wind case, and the mean wind case. The wind factor can be produced for two flight levels and for the four seasons. In addition the model can, through its subroutine DISTAN, provide the great circle distance (GCD) between any two points on the globe. Since it produces both wind factors and GCD, it is capable of calculating both the ground speed and the adjusted flying time between points "A" and "B" if given the airspeed.

4.2 Model Assumptions

The WFSM assumes that all routes are great circle routes or can be decomposed into several legs each of which is a great circle. Further, it assumes that climb winds and descent winds play a negligible role in determining the route-mean wind factor; the aircraft is always "at altitude". Since an arithmetic rather than a harmonic mean is used in computing the route-mean wind factor, it is assumed that the wind speed is less than or equal to one-third of the airspeed.

4.3 Model Limitations

The WFSM cannot produce a "forecast" wind factor or a "simulated" wind having a day-to-day variability. Hence, within any given season and for any given altitude, a particular route will always experience the same wind factor, regardless of the passage of time. Mean winds are always substituted for simulated and "forecast" winds. Temperature, aircraft performance, fuel consumption, and other factors considered by typical flight planning models are not included here since the present model deals with wind only.

Operations north of 75°N or south of 60°S are not permitted.

The coarseness of the present 15°-latitude by 30°-longitude grid system precludes use of the model for calculation of operationally realistic wind factors. Some simple modifications to the existing data base and grid system, along with corresponding changes in the software, can remove this limitation.

The following restrictions must be adhered to:

a. No route should be flown directly over either pole.

b. Neither pole should serve as a point "A" or "B."

c. Circumferential or round robin flights in which "A" and "B" coincide will be aborted. Break such flights into smaller segments.

d. Semicircumferential flights in which point "B" is exactly opposite "A" through the center of the earth will also abort. Break such flights into smaller segments.

e. Routes or segments of routes flown directly north or directly south along a longitude line will also abort.

f. At present, the model allows flights only at altitudes 25,000 feet and 35,000 feet.

g. All departure and destination points must lie within the latitudinal range from 75°N to 60°S.

Restrictions f and g were imposed in order to reduce the core storage requirements of the model.

Chapter 5

USE OF THE WIND FACTOR SIMULATION MODEL

5.1 Use as a Subroutine

The Wind Factor Simulation Model is coded as a constellation of seven FORTRAN subprograms as described earlier in Table 3. The key subprogram is subroutine ENRWND, which invokes the other six subprograms as necessary. Thus, the wind factor model is intended to function as a small, fast module within a larger simulation model, such as MAC's COLOSSUS, as shown in Figure 8.

The WFSM communicates with the user's simulation model only through the argument list of the user's call to subroutine ENRWND.* In the user's model, wherever a wind factor is desired, a call should be placed to ENRWND, supplying values for the input arguments. Subroutine ENRWND then takes control, calculates a route-mean wind factor, and uses it to prepare the output argument.

The user's call to subroutine ENRWND should be of the form,

```
CALL ENRWND (FRMLAT, FRMLNG, TOLAT, TOLNG, JULDAT, GMT, FCHRS, IALT, IOPTN,
ASPEED, GSPEED)
```

The user selects calm, mean, or 90-percent worst winds by specifying a wind option (IOPTN) from 0 to 3 (see Table 6), and specifies the season of the year for which he wants winds by stipulating a Julian date (JULDAT) from 1 to 366. The user then specifies the altitude of the aircraft by setting the flag IALT to 1 for 25,000 feet or to 2 for 35,000 feet. The input variable ASPEED indicates the requested airspeed in knots and the output variable GSPEED indicates the calculated ground speed in knots.

5.2 Inputs

Input arguments for subroutine ENRWND are presented in Table 6. Special formatting rules are as follows:

a. Latitudes and longitudes will be in decimal degrees, not the degrees-minutes-seconds system.

b. South latitudes and east longitudes must be negative.

5.3 Output

Output argument for subroutine ENRWND is the variable GSPEED, a real quantity representing the aircraft's ground speed in knots.

*The exception is that users may call subroutine DISTAN directly if they need a great circle of distance, or function HDG if they want an initial great circle distance.

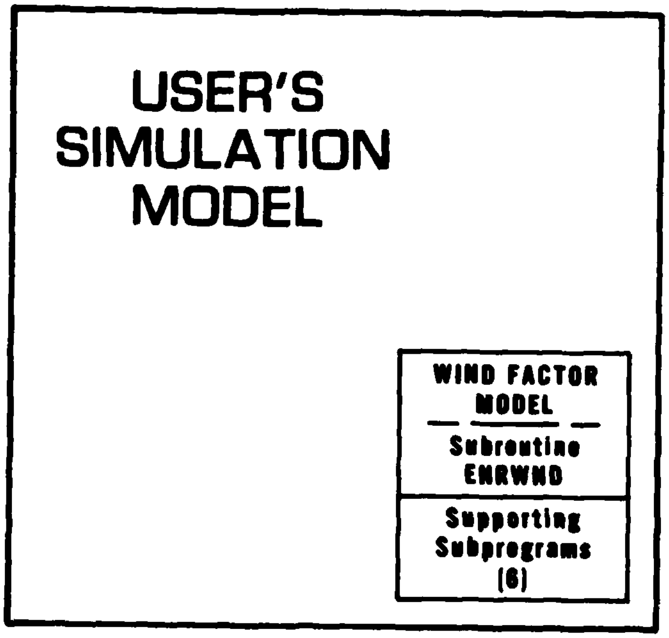

Figure 8. Hierarchy of Models.

Table 6. INPUT ARGUMENTS TO SUBROUTINE ENRWND.

Variable Name	Data Type	Definition	Units/Values
FRMLAT	Real	Latitude of point "A" (Takeoff)	Decimal degrees
FRMLNG	Real	Longitude of point "A" (Takeoff)	Decimal degrees
TOLAT	Real	Latitude of point "B" (Landing)	Decimal degrees
TOLNG	Real	Longitude of point "B" (Landing)	Decimal degrees
JULDAT	Integer	Julian base date of wind factor request	1 - 366
GMT	Real	Greenwich base time of wind factor request	0.0 - 24.0 hrs
FCHRS	Real	Forecast hours ahead	≥ 0.0 hrs
IALT	Integer	Altitude index	1 = 25,000 ft 2 = 35,000 ft
IOPTN	Integer	Wind option or mode	0 = Calm wind 1 = Simulated winds (defaults to 3) 2 = 90-percent worst wind 3 = Mean wind
ASPEED	Real	Airspeed	Knots

Chapter 6

TEST AND EVALUATION OF THE WIND FACTOR SIMULATION MODEL

6.1 Original Tests

The Wind Factor Simulation Model was tested over 36 routes. The first 22 test routes were devised by the model development team. They were designed to test the great circle navigation capability of the model. Consideration was given to using test routes that would approximate the different types of flights used by COLOSSUS. However, no attempt was made to use actual airfield latitudes or longitudes. At first, simple, within-quadrant flights were run from point "A" to point "B." The flight was then reversed and run from "B" to "A." Gradually the type of flight considered was made more complicated. The more complicated the flight in terms of distance and equatorial and dateline crossings, the more difficult it was to solve the great circle equation. Table 7 provides a listing of all test point coordinates, while Table 8 describes the tests themselves. Test routes are drawn in Figure 9.

TABLE 7. TEST POINT CORRDINATES.

TEST NUMBER	LOCATION OF POINT "A" LATITUDE/LONGITUDE		LOCATION OF POINT "B" LATITUDE/LONGITUDE		ROUTE LENGTH (NM)
1.	60.0N	60.0W	30.0N	100.0W	2408.7
2.	30.0N	10.0W	50.0N	40.0W	1807.4
3.	50.0N	10.0W	30.0N	10.0W	1807.4
4.	10.0N	20.0E	30.0N	50.0E	2063.4
5.	30.0N	50.0E	10.0N	20.0E	2063.4
6.	10.0N	40.0E	40.0N	5.0E	2590.6
7.	40.0N	5.0E	10.0N	40.0E	2590.6
8.	10.0S	10.0W	40.0S	60.0W	3204.7
9.	40.0S	60.0W	10.0S	10.0W	3204.7
10.	10.0S	30.0W	40.0S	10.0W	2093.1
11.	40.0S	10.0W	10.0S	30.0W	2093.1
12.	20.0S	20.0W	50.0S	70.0E	2968.3
13.	50.0S	70.0E	20.0S	20.0E	2968.3
14.	50.0S	30.0E	10.0S	50.0E	2599.2
15.	10.0S	50.0E	50.0S	30.0E	2599.2
16.	35.0N	30.0E	50.0N	10.0E	1955.5
17.	20.0S	40.0E	10.0N	20.0W	3975.5
18.	20.0S	30.0W	10.0S	10.0E	2449.0
19.	20.0N	10.0E	10.0S	20.0W	2527.3
20.	10.0N	170.0W	15.0S	165.0E	2113.2
21.	30.0N	135.0E	45.0S	120.0W	7252.8
22.	45.0S	120.0W	30.0N	135.0E	7252.8
23.	46.94N	67.88W(LIZ)	52.37N	0.47E(EGUN)	2575.9
24.	52.37N	0.47E(EGUN)	46.95N	67.88W(LIZ)	2575.9
25.	35.75N	139.35E(RJTY)	38.27N	121.93W(SUU)	4480.0
26.	38.27N	121.93W(SSU)	35.75N	139.35E(RJTY)	4480.0
27.	35.75N	139.35E(RJTY)	13.58N	144.92E(PGUA)	1364.6
28.	13.58N	144.92E(PGUA)	37.75N	139.35E(RJTY)	1364.6
29.	41.12N	95.90W(OFF)	35.05N	106.62W(ABG)	623.3
30.	35.05N	106.62W(ABQ)	41.12N	95.90W(OFF)	623.3
31.	32.50N	93.67W(BAD)	41.12N	111.97W(HIF)	1017.5
32.	41.12N	111.97W(HIF)	32.50N	93.67W(BAD)	1017.5
33.	35.75N	139.35E(RJTY)	23.80S	133.90E(ASIS)	3588.7
34.	23.80S	133.90E(ASIS)	35.75N	139.35E(RJTY)	3588.7
35.	63.97N	22.60W(BIKF)	61.30N	149.80W(EDF)	2920.5
36.	61.30N	149.80W(EDF)	63.97N	22.60W(BIKF)	2920.5

TABLE 8. WIND FACTOR SIMULATION MODEL TESTS.

TESTING SESSION \ TEST NUM	1	2	3	4	5	6	7	8	9	10	11	12
A	F	S	S	S	S	S	S	F	F	S	S	S
B	F	S	S	S	S	S	S	S	S	S	S	S
C	S	S	S	S	S	S	S	S	S	S	S	S
D	S	S	S	S	S	S	S	S	S	S	S	S
E	S	S	S	S	S	S	S	S	S	S	S	S
F	S	S	S	S	S	S	S	S	S	S	S	S
	13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
A	S	S	S	S	F	S	S	S	F	F	S	S
B	S	S	S	S	S	S	S	S	F	F	S	S
C	S	S	S	S	S	S	S	S	F	F	S	S
D	S	S	S	S	S	S	S	S	F	F	S	S
E	S	S	S	S	S	S	S	S	S	S	S	S
F	S	S	S	S	S	S	S	S	S	S	S	S
	25	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
A	S	F	F	F	S	S	S	S	F	F	F	F
B	S	S	S	S	S	S	S	S	F	F	S	S
C	S	S	S	S	S	S	S	S	F	F	F	S
D	S	S	S	S	S	S	S	S	F	F	S	S
E	S	S	S	S	S	S	S	S	S	S	F	S
F	S	S	S	S	S	S	S	S	S	S	S	S

S = SUCCESSFUL TEST
F = FAILED TEST

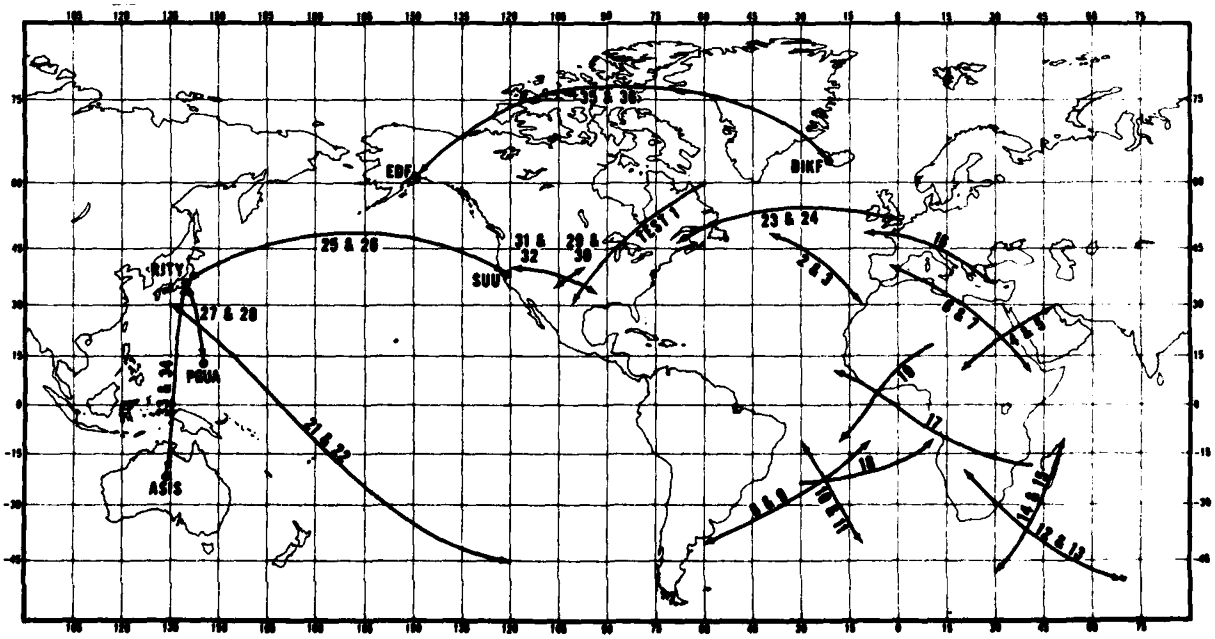

Figure 9. Test Routes.

6.2 Additional Tests

It was the great circle computations (specifically the first guess longitude and the longitude equator crossing calculations) that slowed progress on completing the model. In addition, 14 more test runs were recommended by the Aerospace Sciences Branch of USAFETAC. These new tests were different from the original 22 in that specific COLOSSUS terminals were used as points "A" and "B." While the original 22 tests were successful (20 of 22 were successful the first week; see Table 7 and Figure 9), the new tests posed a greater challenge. In fact, seven of the 14 failed the first time they were run.

These failures caused problems not just with the specific run that failed, but also with earlier successful runs. Debugging a particular test run often inadvertently caused previously successful runs to fail. Consequently, the development team had to test every one of the 36 runs whenever any changes were made in the wind factor program code.

Midway through the test procedure, the wind factor module passed 32 of the 36 test runs. Two of the unsuccessful runs were test 21, (30.0°N, 135.0°E) to (45.0°S, 120.0°W), and its reverse, test 22. The other two unsuccessful tests were numbers 33 and 34. Tests 33 and 34 are the Yokota AB, Japan (35.8°N, 139.4°E) to Alice Springs, Australia (23.8°S, 133.9°E) route and its reverse. Test 21/22 was a very long route, over 7000 miles. The route was further complicated by it's crossing both the equator and the dateline. Test 33/34 was complicated in that it, too, was long and crossed the equator, but more so in that it was almost a due north-south route. In fact, the 3588 miles were traversed with a longitudinal variation of less than 6 degrees. This lack of longitudinal variation approaches one of the limitations in the wind factor module, i.e., a direct north-south route is not allowed and will abort the program.

6.3 Problems Encountered

In these more complicated tests, flights proceeded normally until they reached the equator. At that point the aircraft appeared to "jump" from the equator to point "B" ignoring the intervening grid crossings. For example, the flight from Yokota to Alice Springs (test 33) picked up the points from Yokota southward to the equator but then "jumped" from the equator to Alice Springs. Thus, it picked up points at Yokota, (30.0°N, 138.7°E), (15.0°N, 137.2°E) and the equator crossing (0.0°, 136.0°E). It then "jumped" from the equator crossing to Alice Springs, missing the point at (15.0°S, 134.7°E). When the route was reversed (test 34), the module picked up the points from Alice Springs northward to (15.0°S, 134.7°E) and then to the equator crossing where it "jumped" to Yokota, thus missing the points at (15.0°N, 137.2°E) and (30.0°N, 138.7°E). Since these points are actually grid crossings or crossings of boundaries of the wind factor grid sectors, their mean wind contributions to the calculation of the overall wind factor were being ignored. Even though a route wind factor was produced it was in error.

These errors were corrected by reversing the direction of the spherical triangle as the aircraft crossed the equator. This change solved the problem, and all four of these test runs were successful. However, when the entire 36 tests were run, test 35 (Keflavik, Iceland, to Elmendorf, Alaska) failed. The problem here involved a bad computation of the fictitious equator crossing. Once the problem was isolated and corrected, all 36 tests were run again, this time successfully.

Chapter 7

APPLICATIONS

7.1 Use in COLOSSUS

The Wind Factor Simulation Model was designed to a response to a simulation requirement of the Military Airlift Command (MAC). The wind factor module was needed as an element of the Military Airlaft Command Resource Optimization (MACRO) M-14 simulation project called COLOSSUS, which attempts to simulate the capability of Military Airlift Forces to respond to a real world contingency anywhere, anytime.

7.2 Potential Use in Other Simulators

Although designed in response to MAC's COLOSSUS requirement, the WFSM is general enough to make it useful for other purposes and flexible enough to give it growth potential. Other simulators that require wind factor information may be able to make use of the present model quite easily. As resources for conducting real world tests and exercises gradually decrease, the advantages of simulation grow more apparent. Since the very concept of simulation is to model real world events representatively, it follows that including weather in simulation of environmentally sensitive Air Force operations is advisable. As Air Force simulation models become more complex and more representative of the real world, requirements such as that of COLOSSUS will increase in number and grow in complexity.

7.3 In-house Fast Response Wind Factor Capability

USAFETAC receives many requests for flight planning information and wind factors. At present an in-house computer program is used to respond to these requests. While that method is proven and has been in use for a couple of years, it is costly in terms of computer run time and core storage. With improvements in resolution, the WFSM may prove to be an economical replacement in many cases for the existing wind factor program.

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Appendix A

SPHERICAL AND GLOBAL COORDINATE SYSTEMS

A special orthogonal curvilinear coordinate system, the spherical coordinate system uses coordinates

r = radius	$r \geq 0$
θ = colatitude	$0 \leq \theta \leq \pi$
φ = azimuth	$0 \leq \varphi \leq 2\pi$

The spherical coordinates (r, θ, φ) are related to global coordinates $(a + z$, LAT, LNG), where

a = radius of earth	
z = height above earth's surface	
LAT = Latitude	$-\frac{\pi}{2} \leq \text{LAT} \leq \frac{\pi}{2}$
LNG = Longitude	$0 \leq \lvert\text{LNG}\rvert \leq \pi$

by

$$\left.\begin{array}{ll} r = a + z \approx a & \text{(shallow approximation)} \\ \theta = \frac{\pi}{2} - \text{LAT} & \\ \varphi = -\text{LNG} & \text{for LNG} \leq 0 \\ \varphi = 2\pi - \text{LNG} & \text{for LNG} > 0 \end{array}\right\} \qquad \text{(A-1)}$$

$$\left.\begin{array}{ll} a \approx r & \\ \text{LAT} = \frac{\pi}{2} - \theta & \\ \left.\begin{array}{ll} \text{LNG} = -\varphi & \text{for } \varphi < \pi \\ \text{LNG} = 2\pi - \varphi & \text{for } \varphi \geq \pi \end{array}\right\} & \text{for } \lvert\varphi\rvert < 2\pi \end{array}\right\} \qquad \text{(A-2)}$$

where π = 3.1415927 radians = 180°

1 radian = 57.295780 degrees

1 degree = 0.017453 radians

To convert from global coordinates to spherical coordinates, equation set (A-1) is used. To convert from spherical coordinates to global coordinates, equation set (A-2) is used. Since $r \approx a$, the conversions are between θ and latitude, and φ and longitude.

Spherical coordinate φ is the azimuth angle and is measured in radians counterclockwise from Greenwich looking down from space onto the North Pole. The absolute value ranges from 0 to 2 π radians. Negative values indicate clockwise. (See Figure A-1).

Spherical coordinate θ is the colatitude angle and is also measured in radians. It is the angle southward from the North Pole and ranges from 0 to π radians.

Global coordinates LAT and LNG are in degrees. South latitudes and east longitudes are negative numbers in keeping with standard convention.

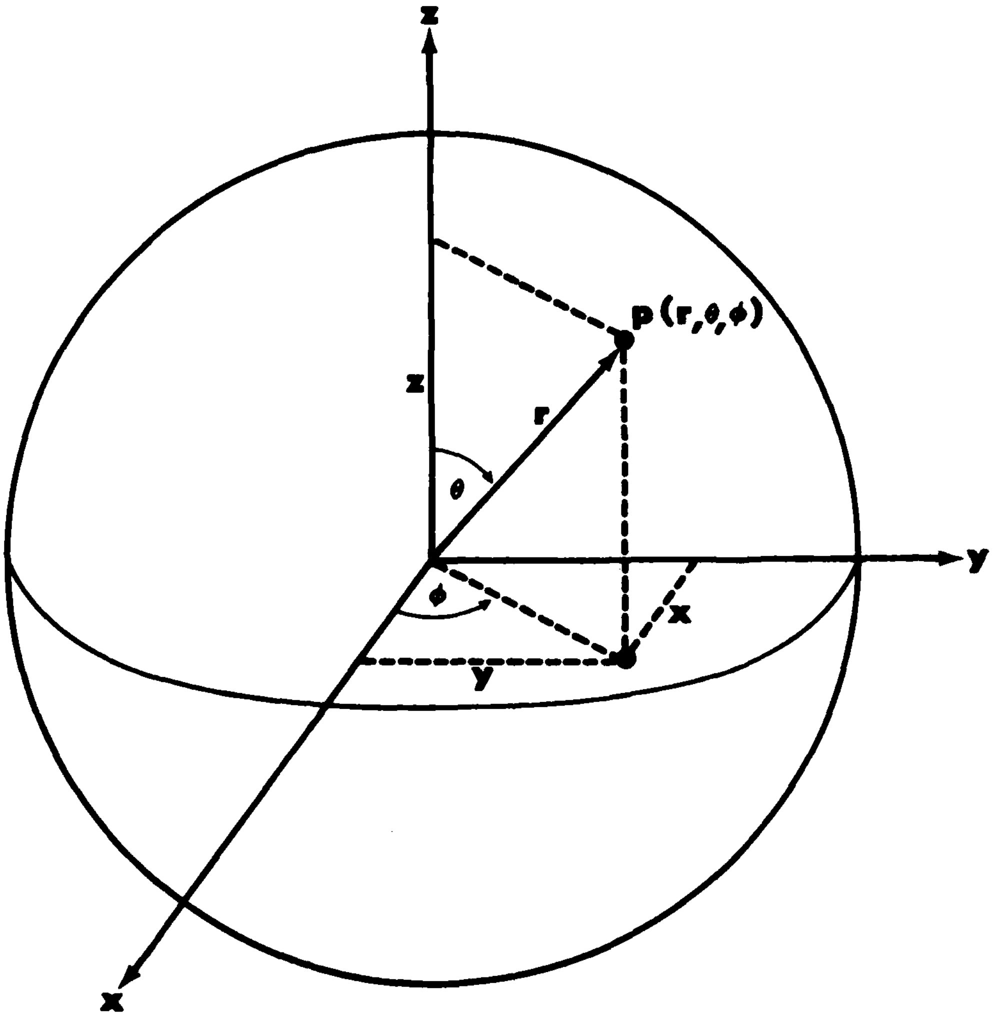

Figure A-1. Spherical Coordinate System.

Appendix B

THE BETA ANGLE

The meteorological wind direction dd can be expressed in the form of a beta angle, β . The beta angle describes the direction toward which the wind is blowing (heading) in terms of radians counterclockwise from eastward (90°).

This system is different from the conventional method of indicating wind direction. The usual manner is to express wind as a direction from which the wind is blowing. The advantage in using the beta angle scheme is that calculations involving aircraft heading and beta angle wind direction (a heading direction) are more easily handled when the frame of reference is directionally the same.

The following illustration serves to show the relationship between conventional wind direction and the beta angle method of indicating wind direction.

Direction Toward Which (0° = N, 90° = E, etc.)	Beta Angle (degrees) (CCW from Eastward)	Beta Angle (Radians)
300.0	-30.0	-0.524
270.0	0.0	0.000
240.0	30.0	0.524
180.0	90.0	1.571

The wind direction toward which, when added to the beta angle, will always equal 270 degrees.

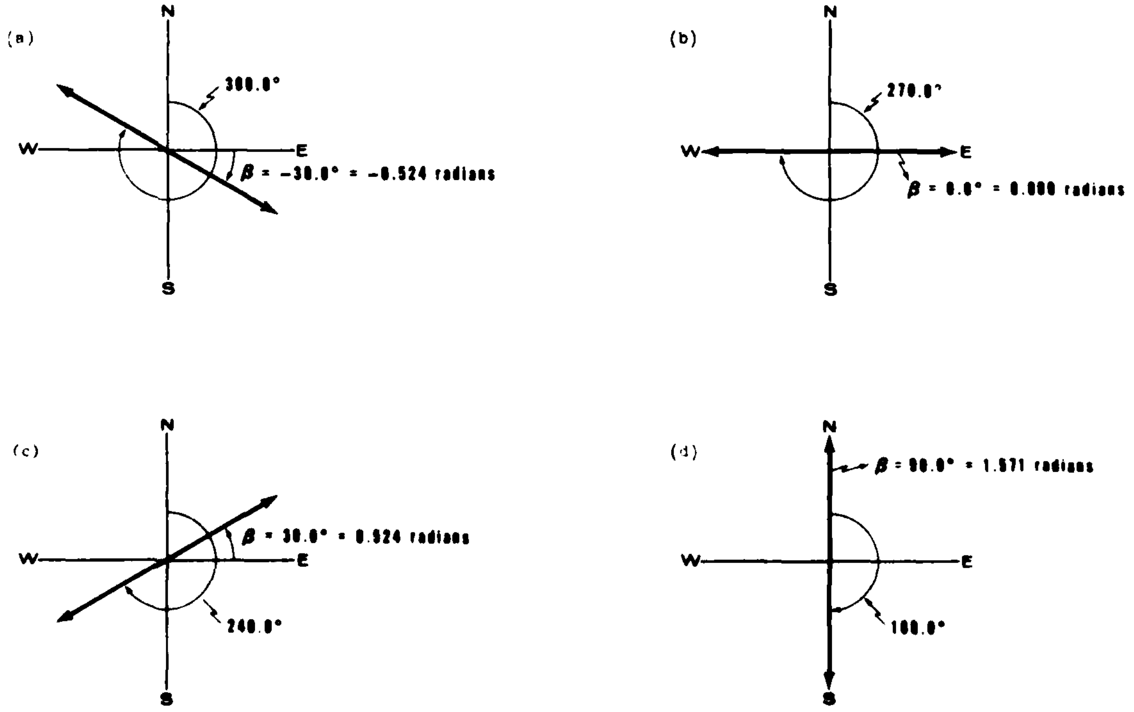

Figure B-1. Beta Angle Illustrations.

LIST OF ABBREVIATIONS AND ACRONYMS

ASPEED	airspeed
BRLNG	FORTRAN subprogram
BRLAT	FORTRAN subprogram
COLOSSUS	MAC airlift system simulation
COMMON	Area of computer storage shared between the main program and its subprograms
CPU	Central processing unit
DISTAN	FORTRAN subprogram
DIRM	wind direction
ENRWND	FORTRAN subprogram
FCHRS	forecast hours ahead
FORTRAN	Formula Translation Language, a computer language suitable for scientific problem solving
FRMLAT	from latitude
FRMLNG	from longitude
GCD	great circle distance
GRTCIR	FORTRAN subprogram
GSPEED	ground speed
GMT	Greenwich Mean Time
HDG	FORTRAN subprogram
HDGM	aircraft heading at location (XLATM, XLNGM)
HP	Hewlett-Packard Company
IALT	Altitude index
ISEASN	season index
IOPTN	wind option
JULDAT	Julian Date
MAC	Military Airlift Command
MACRO	Military Airlift Command Resources Optimization
NM	Nautical miles
NRND	record number
NSEC	grid sector number
SIOP	Single Integrated Operation Plan
SPHGLO	FORTRAN subprogram

SNP	distance between Current-Point and Next-Point
SPDM	wind speed
TOLAT	to latitude
TOLNG	to longitude
USAFETAC	United States Air Force Environmental Technical Applications Center
VARM	wind variance at location (XLATM, XLNGM)
VGM	along-ground-track wind component at location (XLATM, XLNGM)
VCM	cross-ground-track wind component at location (XLATM, XLNGM)
VGACC	sum of along-track component for leg times leg length
VCACC	sum of cross-track component for leg times leg length
VACC	sum of wind variance times leg length
WFSM	Wind Factor Simulation Model
WBAR	time-averaged wind factor
WBARBR	route-mean wind factor
XLATC	Latitude of Current-Point
XLNGC	Longitude of Current-Point
XLATNP	Latitude of Next-Point
XLNGAS	Longitude associated with XLATNX
XLATNX	Latitude of Candidate #1 for Next-Point (next latitude crossing)
XLNGNX	Longitude of Candidate #2 for Next-Point (next longitude crossing)
XLATAS	Latitude associated with XLNGNX
XLATM	Latitude midpoint
XLNGM	Longitude midpoint